Maintaining Soil Productivity during Forest or Biomass-to-Energy Thinning Harvests in the Western United States

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ABSTRACT

Forest biomass thinnings, to promote forest health or for energy production, can potentially impact the soil resource by altering soil physical, chemical, and/or biological properties. The extent and degree of impacts within a harvest unit or across a watershed will subsequently determine if site or soil productivity is affected. Although the impacts of stand removal on soil properties in the western United States have been documented, much less is known on periodic removals of biomass by thinnings or other partial cutting practices. However, basic recommendations and findings derived from stand-removal studies are also applicable to guide biomass thinnings for forest health, fuel reduction, or energy production. These are summarized as follows: (1) thinning operations are less likely to cause significant soil compaction than a stand-removal harvest, (2) risk-rating systems that evaluate soil susceptibility to compaction or nutrient losses from organic or mineral topsoil removal can help guide management practices, (3) using designated or existing harvesting traffic lanes and leaving some thinning residue in high traffic areas can reduce soil compaction on a stand basis, and (4) coarse-textured low fertility soils have greater risk of nutrient limitations resulting from whole-tree thinning removals than finer textured soils with higher fertility levels.

Keywords: thinning, best management practices (BMP), site productivity, soil management

Many forest stands in the western United States are in need of restoration for a variety of attributes (e.g., fire regimes or watershed health) because of fire suppression or lack of harvesting activities (Weatherspoon and Skinner 2002). Precommercial thinnings are often used to restore ecological function and reduce fire hazard in these stands, if trees are too small to have commercial value (Thibodeau et al. 2000). There is also increased interest in harvesting both small and large trees to fuel biomass energy plants or use as feed stock for in-woods energy processing (bio-oil/bio-char) facilities (Laird 2008). For example, there are 6 fully operational Fuels for Schools facilities (Fuels for Schools 2006), 11 facilities under construction, and approximately 47 sites have had prefeasibility assessments completed (Nicholls et al. 2008). Other projects to create clean energy from biomass on a variety of scales are underway throughout the West (Rummer et al. 2003, Skog et al. 2006). It has been estimated that bioenergy production could potentially supply up to 10% of the US energy demand (Nicholls et al. 2008). By producing biomass for energy, land managers may partially offset costs of forest restoration or make harvests more commercially viable. However, it is important that soil quality, function, and productivity potential are maintained during these thinning activities to maintain a steady supply of biomass for future harvests.

Since the passage of the National Forest Management Act in 1976 and related legislation, National Forestlands must be managed to maintain their productive potential, as shown through implementation, effectiveness, and validation (research) monitoring. In addition, the various sustainable forestry certification systems (e.g., Sustainable Forestry Initiative and Canada's National Standard for Sustainable Forest Management) also have criteria and indicators pertaining to maintaining soil productivity on industry or other publicly owned lands. Although the impacts of intensive timber removal (e.g., whole-tree harvesting) on soil properties are generally known, much less is known on the impact of thinning harvests on long-term soil productivity (LTSP; Powers 2006). Suitable measures of soil productivity and site sustainability are also needed, because questions are being raised on the impacts of increased biomass removal from western forests to reduce fire risks and increase energy production from biomass fuels.

Organic matter (OM) in woody debris, forest floor detritus, and the mineral soil is essential for maintaining ecosystem function by supporting soil carbon cycling, nitrogen (N) availability, gas exchange, water availability, and biological diversity (Jurgensen et al. 1997, Page-Dumroese and Jurgensen 2006). Removal of forest OM for biomass energy production or fuel reduction can be accomplished by stand removal (clearcut harvesting), but also by thinning even- and uneven-aged stands (DeLuca and Zouhar 2000). Although the impacts of stand removal on soil properties in the western United States have been documented (e.g., USDA 1980, 1981), much less is known on periodic removals of biomass by thinnings or other partial cutting practices. Loss of OM from periodic stand disturbances, such as thinning, could have negligible short-term impacts (Sanchez et al. 2006) or more significant impacts depending on soil type, tree species, ecosystem, or climatic regime (Henderson 1995, Grigal and Vance 2000).

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Soil productivity is a complex interaction of physical, chemical, and biological processes. Unfortunately, the effects of biomass removal on these processes are not well understood or easily measured (Powers 2006). For example, removing logging slash from forest stands for biomass production, rather than leaving the harvest residues on site, can change nutrient availability (Sinclair 1992), soil temperature, water availability, and biological activity (Harvey et al. 1976, Covington 1981). Conversely, excess biomass left after stand or thinning operations may negatively impact soil quality by providing fuel for uncharacteristically severe wildfires. In this article we discuss the possible impacts on forest thinnings or biomass-to-energy harvests on soil properties and productivity and management practices that could alleviate possible negative impacts.

Soil Physical Properties

Most of the thinning-related impacts on soil physical properties would likely be from compaction. Similar soil disturbance characteristics could occur in clearcut harvesting as in thinning if ground-based equipment is used, although traffic patterns are likely to be different (Miller and Anderson 2002, Chanasyk et al. 2003, McIver et al. 2003). In a review of soil compaction studies, Greacen and Sands (1980) concluded that both clearcut harvesting and thinning are forest management practices most likely to cause soil compaction, although little quantitative data of thinning impacts on soil compaction were given.

Compaction decreases soil porosity; reduces the movement of air, water, and nutrients through the soil; and negatively impacts microbial activity, all of which can reduce tree growth (Brussard and van Faasen 1994, Thibodeau et al. 2000, Bulmer and Simpson 2005, von Wilpert and Schäffer 2006). The susceptibility of soil to compaction is a function of rock content, soil texture, original bulk density (Williamson and Neilson 2000, Powers et al. 2005, Page-Dumroese et al. 2006), soil moisture (Moehring and Rawls 1970, Froehlich 1978), whether the soil is frozen or has adequate snowpack (Curran 1999), and soil OM content (Adams 1973, Howard et al. 1981). For instance, Page-Dumroese et al. (2006) noted that soils with an initial low bulk density and fine texture were more susceptible to machine trafficking than were soils with a high initial bulk density and coarse texture. Machine operator technique also has a strong influence on the degree and extent of soil compaction (Heninger et al. 1997), as well as the number of machine passes (Soane 1990), the type of machine applying the load (Han et al. 2006), and the amount of slash on the site (Curran 1999, Bock and Van Rees 2002).

Many studies have shown compaction effects on soil physical properties from a variety of stand-management techniques in western forests (e.g., Miller and Anderson 2002, Page-Dumroese et al. 2006, Powers 2006), which caused different degrees of reduction in tree growth and health on both fine- and coarse-textured soils (e.g., Froehlich et al. 1986, Conlin and van den Driessche 1996, Heninger et al. 2002). However, in some soils (e.g., coarse-textured, low bulk density soil, and high OM content), compaction had no detrimental impact, or increased growth by decreasing pore size and thereby increasing available water-holding capacity (Gomez et al. 2002, Powers et al. 2004, Ares et al. 2005).

In contrast to many stand-removal studies, relatively few studies have addressed the effects of thinning western forests on soil compaction. In northeastern Washington, Landsberg et al. (2003) showed that thinning an overstocked mixed-conifer stand with harvesters and feller-bunchers increased soil bulk density 3–14% on skid trails but was dependent on slope. Steep units had less off-trail increases in soil bulk density than flat units because equipment was usually confined to trails on steep slopes. In a study in northeastern Oregon mixed-conifer stands, thinning by both skyline and harvester/forwarder methods caused $<$10% topsoil displacement and compaction (McIver et al. 2003). Significant soil compaction was only found within landings, trails, and corridors, whereas soil displacement was found adjacent to the trails. Overall, the few studies on thinning operations in western forests indicate soil compaction is usually concentrated in harvest traffic lanes, when compared with clearcut harvesting, where compaction is often more dispersed.

Stand-harvesting operations may also cause soil puddling (smearing the soil pores to alter soil structure and prevent infiltration), churning (rearranging soil particles), rutting, and loss of the top mineral soil layer (Heninger et al. 2002). Displacement or loss of surface OM and the creation of ruts (depressions made by tires, usually under wet conditions) can disrupt hydrologic cycles on a site and route water down the rut rather than into the soil profile. Ruts and displacement of surface OM can accelerate soil erosion and reduce off-site water quality (Curran 1999). These soil disturbances can be more detrimental to tree growth than soil compaction and should be addressed separately when evaluating harvesting or thinning impacts on soil productivity (Heninger et al. 1997). One method to reduce detrimental impacts is the use of a risk-rating system for evaluating site sensitivity to ground-based harvest activities. Risk-rating systems may help determine which soils and sites may have the greatest potential of loss of productivity due to compaction, ruts, soil displacement, and more. (BC Ministry of Forests 1999). However, we could not find information on thinning studies that addressed changes in physical properties and their effects on aboveground productivity.

The removal of biomass in stand harvesting can greatly reduce forest floor amounts, lower soil OM concentrations, and affect soil physical properties (Standish et al. 1988, Henderson 1995). Such OM-induced changes in soil physical properties may be more important for soil productivity than nutrients removed in the biomass (discussed in the next section). For example, losses of forest floor and mineral soil OM after stand harvesting lowers soil moisture retention, cation-exchange capacity, and subsequent tree growth in coarse-textured soils (Ginter et al. 1979, Ballard and Will 1981, Farrell et al. 1986). Unfortunately, we could find no thinning studies that examined this possibility in western forests. Although it is unlikely that one thinning would remove enough OM to cause such soil changes, repeated thinnings over the life of the stand might impact some soils and needs to be researched.

Soil Chemical Properties

Many studies have been conducted on nutrient removal from stand harvesting, especially clearcutting, and the possible impact on soil productivity. Most of this research was conducted in eastern and southern forests and primarily focused on whole-tree harvesting being used to increase wood supply for the paper products industry (Bormann and Likens 1979, Tritton et al. 1987). Whole-tree harvests are thought to be potentially more detrimental to soil productivity than bolewood-only harvests, because they remove branches, twigs, and foliage that contain high concentrations of most nutrients (Tritton et al. 1987, Palviainen et al. 2004). The loss of the forest floor after stand harvesting and site preparation also can reduce soil nutrient pools and availability (e.g., Thibodeau et al. 2000, Powers et al. 2005, Sanchez et al. 2006). Knowing the total amount of nutrients removed in a thinning operation and the size of the soil pools would facilitate a management plan to replace or retain nutrients (Compton and Cole 1991, Page-Dumroese and Jurgensen 2006). This information is usually not readily available to managers and detailed data are costly to obtain; however, estimates can be made based on biomass removal levels and soils data within the literature.

A possible reduction in soil productivity caused by nutrient removal in total-tree harvesting has been addressed in best management practice (BMP) guidelines issued by several states and summarized in Evans and Perschal (2009). For example, Minnesota BMPs place a restriction on biomass harvesting on infertile, coarse-textured soils (Sustaining Minnesota Forest Resources 2007). Here, it is assumed that mineral weathering in coarse-textured soils will not be sufficient to replace nutrients lost from harvesting (Morris 1997). Fertilization is being used in many places to reduce nutrient removals during thinning and whole-stand harvesting, with N being the nutrient most often applied (Ballard 1979, Weetman et al. 1980, Grier et al. 1989). However, fertilization does not alleviate short-term soil OM losses. Many studies have been conducted on the effects of fertilizing thinned stands (e.g., Brix 1983, Binkley and Reid 1984), and most report tree or water quality response (Binkley et al. 1999), but not soil impacts. In general, stand response to thinning and fertilization appears to be dependent on the initial nutrient status of the soil, soil physical properties after harvesting, climatic conditions, stand age, and the season of application (Grier et al. 1989). Usually, both N fertilization and forest thinning are thought to shorten rotations of individual stands (Weetman et al. 1980) but do not necessarily raise the potential productivity of a site (Miller 1981). However, recent data on the long-term impact of N fertilization shows that low-quality sites could benefit from N fertilization and potentially increase site productivity (Footen et al. 2009). Unfortunately, there is little information available on the effects of forest thinning and subsequent fertilization on soil productivity and nutrient pools in the western United States.

Soil Biological Properties

Nitrogen is often the nutrient most limiting tree growth in western forest soils (Binkley 1991). Because nearly all soil N is present as organic forms, N availability (as NH_4 and NO_3) is dependent on soil microbial activity. Consequently, many studies have examined the effects of stand harvesting on OM decomposition and resulting N mineralization. Generally, the initial loss of surface OM and canopy cover raises soil temperatures, which increases OM decomposition and N mineralization rates (Smethurst and Nambiar 1990, van Cleve et al. 1983, van Cleve and Yarie 1985). However, if large amounts of logging slash are left after the harvest, N can be immobilized in microbial biomass until the residues are decayed (Powers 1989, Thibodeau et al. 2000).

Similar changes in N mineralization could also occur after thinning operations (Grady and Hart 2006), but the degree and extent would depend on how much of the stand biomass (thinning intensity) was removed from the site. For example, slash left on site after thinning ponderosa pine stands in western Montana caused little change in microbial biomass, total N, and potentially mineralizable N (DeLuca and Zouhar 2000). In stands thinned of approximately 40% of their basal area, mineral soil mineralizable N amounts were significantly less than in unharvested stands (Grady and Hart 2006). Initial soil N content is also a factor, because thinning a low fertility balsam fir (*Abies balsamea*) site in Canada resulted in greater N mineralization than on a site with higher nutrient status (Thibodeau et al. 2000).

One concern of biomass harvesting is that it will adversely impact the amount of coarse-woody debris (CWD) remaining on a site. Ectomycorrhizal root development is strongly related to stand productivity in many western forest ecosystems (Harvey et al. 1980, Perry et al. 1989), and harvesting often results in a decline of both fine root activity and ectomycorrhizal fungi diversity (Hagerman et al. 1999). Loss of organic horizons or CWD during and after harvests is a possible cause for such reductions in mycorrhizae (Jurgensen et al. 1997). CWD is also important for animal and microbial diversity (Prescott and Laiho 2002, Pyle and Brown 2002), and possibly site productivity (Grigal 2000). Coarse wood and retention requirements are listed in the Washington BMPs and primarily focus on wildlife benefits rather than soil productivity potential (Washington Department of Natural Resources [DNR] 2007). Many land-management agencies and industries have guidelines that require leaving some volume of CWD after harvest, but these do not directly address biomass thinnings or partial cuts. However, it is unlikely that large OM losses and removal of large trees suitable for CWD retention would occur from thinning operations.

Management Implications

As we have shown, considerable information is available on the impacts of stand removal on soil physical, chemical, and biological properties. The degree and extent of these impacts will vary depending on manageable factors, such as equipment configuration and use; soil moisture levels at the time of harvest activity; season and weather conditions during harvest; and inherent site sensitivity (risk) as defined by soil texture, coarse fragment content, OM content, and fertility. Together, they dictate the severity and extent of logging operations on soil physical, chemical, or biological properties (Gundale et al. 2005, Moghaddas and Stephens 2007, 2008). It is also clear that much less information is available on the effects of biomass thinning on soil properties, especially in western forests. However, many findings derived from stand-removal studies are also applicable to guide biomass thinnings for forest health, fuel reduction, or energy production. These can be summarized as follows:

1. **Thinning operations are less likely to cause significant soil compaction than with a stand-removal harvest.** However, this would depend on harvest method (e.g., skidder impacts > forwarder cut-to-length), amount of residual slash left in traffic lanes, operator technique, soil condition and properties (wet, shallow to bedrock, coarse textured, and so on), and climate (Senyk and Craigdaillie 1997, Heninger et al. 2002, Han et al. 2009). For example, winter logging on frozen soils (where this occurs), or summer logging when soils have lower soil water content, would likely reduce soil compaction and surface rutting and protect fine roots (Williams and Buckhouse 1993, Bock and Van Rees 2002, Page-Dumroese et al. 2006). Conversely, wet season harvesting can cause deep ruts or puddled soils that result in water either ponding on site or being routed off-site by ruts. Soil disturbance that causes a change in water flow patterns should also be avoided (e.g., blocking natural drains and impounding water). The impact of soil compaction on site productivity is also tree species dependent. Ten-year results from a North American LTSP study site in Idaho

Table 1. Some key references and decision-support tools for meeting soil management objectives for biomass removals in the western United States.

Soil disturbance	Reference(s)	BMPs	Tools
Disturbance keys	Napper et al. (2009)	Forest practices monitoring	Soil disturbance picture guide (US forests)
	Page-Dumroese et al. (2009)	Soil disturbance monitoring	How-to guide for transect or point monitoring, worksheets, disturbance classes
	Scott (2007)	Ground-based forest practices	Soil disturbance classification
	BC Ministry of Forests (1999)	Forest practices and risk rating	Soil Conservation Surveys Guidebook (BC Ministry of Forests and Range)
	Herrick et al. (2000)	Rangeland monitoring	Transect monitoring
Thinning	Eliasson and Wästerlund (2007)	Reduce rutting and compaction	Slash mats
	Han et al. (2006)	Ruts and soil moisture	Slash mats
	Bulmer and Krzic (2003)	Skid trails and landings	Rehabilitation
	Block et al. (2002)	Compaction and disturbance regimes	Landscape scale analyses
	Williams and Buckhouse (1993)	Winter logging	Snow depth
Soil management	Helgerson and Miller (2008)	Maintaining healthy and productive soils	General BMPs
Maintaining OM	Heninger et al. (2002)	Ground-based harvesting	Risk ratings

indicated that growth of western white pine (*Pinus monticola*) seedlings were more sensitive to severe compaction than Douglas-fir (*Pseudotsuga menziesii*) seedlings (Page-Dumroese, unpubl. data, 2003).

2. **Use of a risk-rating systems can identify soil conditions that may result erosion, compaction, or soil OM removal.** BMPs have been developed by some states, Canadian provinces, and companies to minimize or avoid detrimental impacts to soil quality or stand growth. However, if not available, the key references and decision-support tools provided in Table 1 can be used as general guidelines.
3. **Use of designated or existing harvest traffic lanes during biomass thinnings and leaving thinning residue in high traffic areas can reduce soil compaction on a stand basis.** Concentrating thinning operations on harvest traffic lanes can minimize the areal extent of soil compaction and other changes in soil physical properties throughout the stand (Curran et al. 2005, Moghaddas and Stephens 2008). In areas where designated harvest lanes are not feasible or desirable, avoid removal of surface OM and mineral topsoil to protect soil quality and maintain nutrient cycling. Traffic lanes should be located to avoid damaging sensitive areas or disrupting natural drainages. Leaving thinning residue will also minimize detrimental soil compaction (Han et al. 2006, Moghaddas and Stephens 2008, Han et al. 2009) and help maintain soil OM levels, increase N cycling, and promote mycorrhizae development. Logging slash and surface OM also reduce soil temperature, increase soil moisture available throughout the growing season (Carey et al. 1981), are weed barriers (McDonald and Helgerson 1990), and reduce erosion (Blackburn et al. 1990, Chanasyk et al. 2003). Coarse wood can support both macro- and microfauna diversity and in some areas is required by forest practice regulation (Washington Department of Natural Resources [DNR] 2007). Care must be taken to balance the benefit of leaving OM to maintain soil productivity with the increased risk of high-intensity wildfires. However, this would likely not be a problem unless whole-tree thinning is used.
4. **Low fertility, coarse-textured soils are at greater risk of nutrient limitations caused by whole-tree thinning harvests than high fertility soils with finer textures.** However, very little is known about how often this occurs and how this might vary with soil parent material (Garrison et al. 2000). Therefore, the impact of using whole-tree harvesting on western soils or allowing leaves and needles to fall off branches before removing biomass on long-term soil productivity is unclear (Fahey et al. 1991, Williams and Buckhouse 1993), but potential negative impacts from whole-tree biomass removals will be a greater risk on sites low in OM and N content. If nutrient removals are a concern, limit whole-tree harvesting and consider stand fertilization to improve soil nutrient status and maintain or improve tree growth.
5. **Emerging technologies may help mitigate potential detrimental soil impacts.** New technologies are being tested that may help mitigate the impacts from biomass-to-energy harvesting on soil physical, biological, or chemical properties. For example, in-woods fast pyrolysis is being developed to turn forest biomass into bio-oil with the residual (bio-char) left on site after the operation. Leaving bio-char in the forest may be a sustainable alternative to whole-tree harvesting, because it is hypothesized to increase available water, build soil OM, enhance nutrient cycling, and reduce leaching (Laird 2008). Although the technology sounds promising, much more information is needed on this method and how bio-char affects soil properties and long-term soil productivity. In addition, new cut-to-length and forwarding systems can also be effective in reducing soil compaction as well as providing nutrient-rich branch, foliage, or bark material from trees processed in the traffic lanes.

The focus of these recommendations is to reduce the impact of thinning operations on soil productivity and subsequent stand growth. Using risk-rating systems to determine those sites most susceptible to soil disturbance impacts may be the best way to determine which harvest method and BMP options to implement (Table 1). Although measuring the impacts of thinning on soil properties is relatively easy, determining whether the measured soil changes affect site productivity is difficult. Thinning reduces total stand biomass but increases the growth of individual trees by decreasing competition (e.g., Liechty et al. 1986, Karlsson 2006). If the response of stand productivity to thinning is only measured on the residual trees, any negative impact of thinning on soil properties could be masked by the increased growth of the remaining trees. We could not find any studies that attempted to separate soil impacts due to thinning and residual tree growth on total stand productivity.

Numerous studies have shown that the interaction of forest management and inherent site factors elicit differing tree responses (e.g., Greacen and Sands 1980, Senyk and Craigdallie 1997, Heninger et al. 2002). Ideally, baseline tree and soil information is needed before full-scale biomass removal treatments are conducted, so that the magnitude of change and the functions and processes affected can be quantified (Grigal and Vance 2000). However, in many cases, this baseline information might not be available, and recommendations by local specialists, use of Natural Resource Conservation Service soil descriptions and interpretations, or use of information from similar sites elsewhere may be necessary to make inferences on soil productivity changes. If baseline data can be collected on stand response by postharvest monitoring to detect changes in soil properties (Table 1), managers will be in a better position to assess the impacts of biomass removal to improve forest health or for energy production.

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